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FINAL TECHNICAL REPORT

Air-Sea Interaction in Regions of Varying Surface Conditions

ONR Contract N00014-87-G-0191

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1. Introduction

The Frontal Air-Sea Interaction Experiment (FASINEX) was a field experiment that was primarily performed in the Fall of 1985 and Spring of 1986 in the vicinity of the subtropical oceanic front south of Bermuda (Stage and Weller, 1985). Leadership and primary funding for this experiment came from the Office of Naval Research (ONR) with additional funding for some participants coming from several other governmental agencies including NSF, NASA, and NOAA. FASINEX arose from the realization that little data was available about atmospheric and oceanic processes in regions of non-homogeneous sea surface temperature (SST) such as the subtropical SST front south of Bermuda. What data was available indicated that such regions behave significantly differently than homogeneous areas. A more complete discussion of the scientific motivation and objectives fro FASINEX can be found in Stage and Weller (1985) and the experimental field plan in Stage and Weller (1986).

This is a final report on the work done at The Florida State University (FSU) as a part of FASINEX under contract number N00014-87-G-0191 titled Air-Sea Interaction in Regions of Varying Surface Conditions. It must, however, be emphasized that several aspects of this work are being further studied under a newer ONR grant with the same title.

2. Project Goals

The chief goal of this project was to develop an understanding of the behavior of the Marine Atmospheric Boundary Layer (MABL) in the vicinity of the FASINEX SST front. There were two major components to this work:

A. To study turbulent fluxes and other turbulent statistics in the vicinity of the SST front as measured by FASINEX aircraft. Special statistical methods were devised and used to show how these quantities change near the SST front.

B. To study the structure of the MABL in by analysis of results from a two dimensional numerical model. MABL structure was examined as a function of the direction of the synoptic scale geostrophic wind relative to the front. We also looked at the secondary circulations induced in the MABL by the SST front.

3. Project Accomplishments

3.1. Turbulent fluxes near the SST front.

One of the goals of this project was to determine how the turbulent fluxes, variances, and covariances change in the vicinity of the FASINEX SST front. An important question that arises in this non-homogeneous region is how to go about computing these statistics.. Traditional Reynolds fluxes are computed in homogeneous conditions by taking time signals, removing long term variations by high pass filtering or linear trend removal and then computing the variances and covariances. Authors differ in the high pass filters used and in the averaging time used in computing the variances and covariances. In non-homogeneous situations these issues become crucial to meaningful interpretation of the data. In homogeneous situations, too short an averaging time results in statistics that do not include all of the important scales of motion and that are subject to high stochastic variability and uncertainty do to an insufficient number of cycles of the significant frequencies. Longer averaging reduces these effects but introduces variance and covariance that is associated with mesoscale or synoptic scale processes. In non-homogeneous cases these same concerns are relevant plus there is the added problem that longer averaging has the undesirable effect of smearing out the changes in turbulent statistics at the front and thus hiding the sharpness of the changes there.

Crescenti (1988) has devised two methods for computing turbulent fluxes, variances, and covariances that faces these problems. The methods consist of computing statistics that depend on position rather than the traditional method of computing a single value. In the first method a

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boxcar running mean filter is applied to the data. Data within the boxcar is linearly detrended and variances and covariances are computed over the length of the boxcar. This technique has the advantage that the value computed is the same as would be found by breaking the data into a block with the same length as the boxcar. It also preserves the usual mathematical properties needed to achieve Reynolds decomposition of the atmospheric budget equations. The second method consists of using an FFT to perform a sharp high pass filter on the data, multiplying the resulting signals and using an FFT-based low pass filter to perform the averaging needed to compute the variance and covariances.

Crescenti showed that these two methods produce similar results. He examined the effects of boxcar length on the fluxes and determined that a boxcar length of 6 km gave the best results. His results show that there are large, rapid changes in MABL temperature variances, heat and vapor fluxes in crossing the SST front. These changes are obtained by changes in the variances of the parameters with little change in correlation coefficients and phase angles. This suggests that turbulence increases intensity without change in eddy structure. A more thorough discussion is contained in Crescenti (1988, abstract attached in the Appendix).

From Crescenti's results it is obvious that the changes in turbulent statistics are strongest when the wind blows across the front from over the cold water to over the warm and least strong for the opposite wind direction. We are now preparing a manuscript (Stage and Crescenti, 1988) that uses the techniques developed by Crescenti (1988) to further study the behavior of atmospheric turbulence in the vicinity of the FASINEX front, especially the dependence on mean wind direction.

Herbster (1990) has used Crescenti's techniques to examine X-Z cross sections of the MABL fluxes. On Feb. 14 the wind was northerly in the FASINEX area and the Naval Research Laboratories (NRL) P3 aircraft flew a stack of 5 legs perpendicular to the SST and having elevations from 100 m to 1800 m. On Feb. 16 the wind was again northerly and the NCAR Electra and the flew the FASINEX flight box in formation. The result is two stacks perpendicular to the front with legs at 35, 100, and 945 m. Herbster's results support and expand on Crescenti's. The abrupt increases in heat flux, variance of vertical velocity, and variance of potential temperature at observed at low levels by Crescenti are seen to shift southward (downwind) and to become less abrupt at higher levels. Convective features that appear on all levels demonstrate the vertical continuity of these features. Given the two plus hours to complete each stack, Herbster's analysis also indicates that these features persist in time.

A manuscript (Stage, *et al.*, 1990) is now being prepared that attempts to meld different studies into a picture of the mean structure of the MABL. Another paper (Friehe, *et al.*, 1990) is also being prepared that draws together the work of several investigators to study the behavior of stress near the SST front. These papers will appear in a special FASINEX edition of the Journal of Geophysics and be bound into a FASINEX monograph. Abstracts of these papers appear in the appendix.

3.2. Numerical Modeling.

The model used for this study was previously developed by Wai. This model consists of the Boussinesq primitive equations, second-order closure for turbulent fluxes, and a long wave radiative model. The model runs in an X-Z plane with the X axis perpendicular to the SST front. The front is assumed to be linear. The model has been modified to have open lateral boundary conditions so that it can be applied to the FASINEX situation. We know of no other such model. We have modified the model code to run on the Cyber 205 supercomputer at FSU and have improved the method used to solve the Poisson equation for pressure. Use of the supercomputer has enabled us to run the model for longer times and thus obtain better steady state solutions.

Results from the model have been reported in several conference papers (Stage, et al.,

1987a, b; Wai and Stage, 1987; abstracts attached as appendices). In these papers we have concentrated on the structure of the MABL for geostrophic winds from the north, east, south, and west. These papers show how mean quantities of the MABL change across the front in each of these four cases and show that each wind direction produces a distinctive secondary circulation. A more detailed discussion of the behavior of the ABL for each of the test cases can be found in the abstracts and the articles.

One frustration in the modeling work has been that the strength of the secondary circulations seen in the model is generally about the same magnitude as the natural stochastic variability of the variables as seen in the data. This makes it difficult to make direct comparisons between the model results and the FASINEX observations, however some aspects of the model results do agree with the data.

4. Further Work

Several aspects of this work are being continued under another ONR grant. Manuscripts are being prepared based on Crescenti's M. S. thesis. Herbster is currently finishing his thesis and expects to be done by the end of Winter semester (April 1990). We will then prepare a manuscript from his results. Although some of this work is simply a matter of polishing text, there are still several aspects of the data that are not well-enough understood. The main challenge remaining is to continue to form a coherent picture of the MABL structure based on the measurements and the model results and, especially to seek further verifications between the data and the model.

5. Publications Under this Grant

5.1. Papers in refereed journals and Thesis.

Crescenti, G. H., 1988: Turbulent Variances and Covariances in the Marine Atmospheric Boundary Layer Over the FASINEX Front. M. S. Thesis, Florida State University, Tallahassee, Florida, 167 pp.

Crescenti, G. H., and S. A. Stage, 1990: Determination of Nonhomogeneous Turbulent Fluxes Near the FASINEX Sea Surface Temperature Front. Submitted to *J. Geophys. Res.*

Friehe, C. A., W. J. Shaw, D. P. Rogers, K. L. Davidson, W. G. Large, S. A. Stage, G. H. Crescenti, S. J. S. Khalsa, G. K. Greenhut, and F. Li, 1990: Air-sea fluxes and surface-layer turbulence around a sea surface temperature front. Accepted by *J. Geophys. Res.*

Herbster, C. G., 1990: The Vertical Structure of the Marine Atmospheric Boundary Layer Across a Sea Surface Temperature Front. M. S. Thesis, Florida State University, Tallahassee, Florida.

Stage, S. A., J. Bates, G. H. Crescenti, K. Davidson, C. Gautier, G. Greenhut, C. Herbster, K. Katsaros, S. J. Khalsa, R. Lind, D. Rogers, W. J. Shaw, and M. K. Wai, 1990: Marine atmospheric boundary layer structure in the vicinity of a sea surface temperature front. Submitted to *J. Geophys. Res.*

Wai, M. M. and S. A. Stage, 1989: Dynamical analyses of the marine atmospheric boundary layer near the Gulf-Stream oceanic front. *Quart. J. Roy. Meteor. Soc.*, **115**, 29-44.

5.2. Conference Papers

(In chronological order.)

Stage, S. A., M. M. Wai , and J. H. Crescenti, 1987: Atmospheric boundary layer structure near an oceanic SST front. Third Conference on Mesoscale Processes. August 21-26 1987. Vancouver, B.C. Canada, American Meteor. Soc., 206-207.

Stage, S. A., M.-K. Wai, and J. H. Crescenti, 1988: Atmospheric secondary flows in the vicinity of an oceanic front. Seventh Conference on Ocean-Atmosphere Interaction. February 1-5, 1988. Anaheim, California, American Meteor. Soc.

Wai, M. and S. A. Stage, 1988: A numerical study of the atmospheric boundary layer near an oceanic front. Eighth Symposium on Turbulence and Diffusion. April 25-29, 1988. San Diego, California, American Meteor. Soc. 309.

6. References

(Other than those listed under publications.)

Stage, S. A., and R. A. Weller, 1986: The Frontal Air-Sea Interaction Experiment; Part II: Experimental Plan. *Bul. Amer. Meteor. Soc.*, **67**, 16-20.

Stage, S. A., J. Bates, G. H. Crescenti, K. Davidson, C. Gautier, G. Greenhut, C. Herbster, K. Katsaros, S. J. Khalsa, R. Lind, D. Rogers, W. J. Shaw, and M. K. Wai, 1990: Marine atmospheric boundary layer structure in the vicinity of a sea surface temperature front. In preparation, to be submitted to *J. Geophys. Res.* (Author order yet to be determined.)

7. APPENDICES

This report includes the following appendices:

Abstract of G. H. Crescenti (1988).

Abstract of Mickey M-K Wai and Steven A. Stage (1989).

Abstract of Herbster (1990).

Abstract of Stage, *et al.* (1990).

Abstract of Friehe, *et al.* (1990).

7.1. Abstract of G. H. Crescenti (1988).

TURBULENT VARIANCES AND COVARIANCES IN THE MARINE ATMOSPHERIC BOUNDARY LAYER OVER THE FASINEX FRONT

Gennaro H. Crescenti, M.S.
The Florida State University, 1988

Major Professor: Steven A. Stage, Ph.D.

A modified moving boxcar average and spectral filtering method are used to determine variances and covariances of meteorological variables in a nonhomogeneous marine atmospheric boundary layer (MABL). The data set analyzed was taken over the Sargasso Sea in the vicinity of an oceanic sea surface temperature front during the Frontal Air-Sea Interaction Experiment (FASINEX) in February 1986 by the NCAR Electra. The meteorological variables analyzed include the longitudinal, lateral and vertical velocities, potential temperature, and specific humidity in a three day case study in which an anticyclonic synoptic weather system north of the experiment area presented three different flow regimes.

The first day (16 February) is marked by a well mixed MABL with winds from the northeast across the front from cold to warm side. The second day (17 February) is also marked by a well mixed but deeper MABL with winds nearly parallel to the front from the east-southeast. The final day (18 February) shows increased atmospheric stability with a very shallow mixed layer with winds coming from the south-southeast across the front from warm to cold side.

Spectral analysis suggests the presence of a spectral gap in the frequency range of 0.0167 Hz or a period of approximately 60 seconds. This time scale is used as an averaging length for the boxcar method and as a cut off period for the spectral method. Each method shows good agreement with the other and displays the extent of the nonhomogeneity of the MABL.

The MABL across the oceanic front is found to be nonhomogeneous. The MABL parallel to the front is found also to be nonhomogeneous but to a lesser extent. Turbulent variances and covariances were found to be maximum when a component of the mean MABL wind blows across the front from the cold to warm side. The variances and covariances are less intense when the mean MABL winds are nearly parallel to the front and minimal when a component of the mean MABL winds blow from the warm to cold side.

7.2. Abstract of Mickey M-K Wai and Steven A. Stage (1989).

Dynamical Analyses of Marine Atmospheric Boundary Layer

Structure Near the Gulf Stream Oceanic Front

by

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SUMMARY

The effects of the sea surface temperature (SST) front at the edge of the Gulf Stream on the marine atmospheric boundary layer (MABL) are investigated using a numerical model to study the modification effects of an oceanic front on the MABL structure. The situation simulated is flow from over cold shelf water to over the warm water of the Gulf Stream. The initial temperature and humidity profiles of the air are specified to be near neutral over the cold water and are therefore typical of undisturbed conditions. The differential in the SST across the oceanic front creates a horizontal variation in the surface perturbation pressure and the stability. The surface perturbation pressure and turbulent fluxes modulate the flow and produce horizontal variation in horizontal wind components with associated vertical motions. A thermally direct cell is produced as a result of the SST difference across the front. The isotherms slope upward towards the warm water. Entrainment of inversion layer air and upward vertical motion over the warm water cause the MABL to be deeper there. A layer of cloud forms over warm water and is associated with mixed layer deepening rather than lowering of the condensation level. Turbulent fluxes in the MABL show considerable spatial variation. Surface stress is much larger over the front and over the warm water than over the cold water. This is mostly caused by wind speed changes associated with the front. Changes in drag coefficient due to changes in surface roughness and stability are much less important.

Mean budgets for temperature and total water indicate that there is a balance between horizontal advection and turbulent flux divergence. The U momentum budget shows that once the geostrophic balance terms are subtracted off, the balance is mainly between the pressure gradient force associated with the induced temperature field and turbulent friction with horizontal advection and the Coriolis force acting on the geostrophic departure playing minor roles. The V momentum budget shows a balance between horizontal advection, Coriolis force and friction.

Although there is little data for comparison, the results are in qualitative agreement with observations in the area. This study shows that the SST front at the Gulf Stream edge produces marked local changes in the nearby atmospheric surface layer.

7.3. Abstract of Herbster (1990).

THE VERTICAL STRUCTURE OF THE MARINE ATMOSPHERIC BOUNDARY LAYER ACROSS A SEA SURFACE TEMPERATURE FRONT.

Christopher G. Herbster, M.S.
The Florida State University, 1990

Major Professor: Steven A. Stage, Ph.D.

The response of the lower marine atmospheric boundary layer to a sharp change in sea-surface temperature was studied in the Frontal Air-Sea Interaction Experiment (FASINEX) with ships and aircraft instrumented for turbulence measurements. The synoptic conditions on the 14th and 16th of February, 1986 presented the opportunity to study the vertical structure of the turbulence for the case of a North wind, blowing from the cold to warm side of the front. A moving boxcar averaging technique (after Crescenti, 1988) was used to determine the turbulent statistics and fluxes for the meteorological variables, and their associated changes, as the air made the transition from the cold to warm side of the front.

The data for this study were obtained from two aircraft, the NCAR Electra and NRL-P3, equipped for turbulence measurements in the atmosphere. The flight tracks for the two days were designed to investigate somewhat different aspects of the marine atmospheric boundary layer, concentrating on either the vertical structure alone (14 February) or on both the vertical and horizontal structure (16 February) in the vicinity of an oceanic temperature front.

The depth of the atmospheric boundary layer was found to be approximately 200 m deeper over the warm water than was found over the cold water. The potential temperature was found to respond very rapidly to the underlying warm water throughout the entire depth of the boundary layer. The increase in temperature was found to occur over a slightly broader region as the altitude was increased.

The vertical heat flux for each of the two days showed a pronounced increase over the warm water. While each day showed this general trend, there were distinct differences for the two days. The heat flux for the 14th showed two organized convective cells in the immediate vicinity of the front, one of which showed evidence of penetration into the inversion layer. This type of organized convection was not found on the 16th.

An analysis of the vertical momentum transfer, or stress, showed a nearly quadrature relationship between the horizontal and vertical velocity fluctuations. The phase relationship between these two variables was found to be more complicated than was found for the heat flux. Regions in the lower boundary layer in which the stress was found to be negative were found to coincide, in general, with regions which had about a 45° phase relationship between the two variables.

The variances of the meteorological variables were found, in general, to increase across the front over the warmer water. Both the vertical velocity and temperature fields showed a vertical structure which was in good agreement with previous boundary layer experiments. For both of these variables the maximum values for the variances were found to lie in the region between 30 and 60% of the depth of the boundary layer.

7.4. Abstract of Stage, *et al.* (1990).

Marine Atmospheric Boundary Layer Structure
in the Vicinity of a
Sea Surface Temperature Front

by

Steven A. Stage , William J. Shaw, Siri Jodha Khalsa,
Gary K. Greenhut, Gennaro H. Crescenti, Carl A. Friehe,
Catherine Gautier, Kenneth Davidson, Kristina Katsaros,
Mickey M-K Wai, David Rogers, Chris Herbster,
Richard Lind, and John Bates

Data from the Frontal Air-Sea Interaction Experiment (FASINEX) and results from boundary-layer models are used to examine the structure of the marine atmospheric boundary layer in the vicinity of a subtropical sea surface temperature (SST) front. Long and short wave satellite images are used to study cloud cover and radiative energy balances in the experimental region. Aircraft radiative and turbulence measurements are used to study changes in mean wind, temperature, humidity and mixed layer depth across the region of the SST front.

The wind direction relative to the SST front was different on each of the three flight days studied here. MABL structure is found to depend on whether the wind crossed the front from the cold to the warm side, was parallel to the front, or crossed it from warm to cold. The SST front was associated with substantial mesoscale features in the marine atmospheric boundary layer (MABL) flow on all three days. During cold-to-warm air flow the heat flux made a sharp transition at the front and a band of cloud was present just south of the front that appears to be connected to the front. A small pool of warm water at the northeast corner of the experimental area also produced substantial effects in the flux and cloud fields. For air flow nearly parallel to the SST front, There was a sharp north-south gradient in potential temperature near the front and little gradient away from the front. Details of the MABL structure near the front depend on small shifts in the relative alignment of the front and the wind. On the day with winds from warm-to-cold, a stable internal boundary layer grew near the surface and cut off turbulent mixing with the upper part of the MABL. Both daily and monthly radiation fields show modification by the SST front. Model computations give general agreement with the aircraft data and provide a helpful framework for interpreting boundary layer behavior.

7.5. Abstract of Friehe, *et al.* (1990).

Air-sea fluxes and surface-layer turbulence
around a sea surface temperature front.

by

C. A. Friehe, W. J. Shaw, D. P. Rogers, K. L. Davidson,
W. G. Large, S. A. Stage, G. H. Crescenti,
S. J. S. Khalsa, G. K. Greenhut, and F. Li

The response of the lower marine atmospheric boundary layer to sharp changes in sea surface temperature was studied in the Frontal Air-Sea Interaction Experiment (FASINEX) with aircraft and ships measuring mean and turbulence quantities, sea surface temperature and wave state. Changing synoptic weather on three successive days provided cases of wind direction both approximately parallel and perpendicular to a surface temperature front. For the wind perpendicular to the front, both wind over cold-to-warm and warm-to-cold surface temperatures occurred. For the cold-to-warm case, the unstable boundary layer was observed to thicken, with increased convective activity on the warm side. For the warm-to-cold case, the surface-layer buoyant stability changed from unstable to neutral or slightly stable, and the sea state and turbulence structure in the lower 100 m were immediately altered with a large decrease in stress and slowing of the wind. Measurements for this case with two aircraft in formation at 30 and 100 m show a slightly increased stress divergence on the cold side. The turbulent velocity variances changed anisotropically across the front: The stream-wise variance was practically unchanged, whereas the vertical and cross-stream variances decreased. Model results, consistent with the observations, suggest that an internal boundary layer forms at the sea surface temperature front. The ocean wave, swell and microwave radar back-scatter fields were measured from several aircraft which flew simultaneously with the low-level turbulence aircraft. Significant reductions in back-scatter and wave height were observed on the cold side of the front.